Burning of Hydrocarbon Fuels Directly in a Water-based Heat Carrier: Toward to a New Principle of Operation of Heat Generators

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Abstract: A principal possibility of burning hydrocarbon fuels directly in a water-based heat carrier is demonstrated. The first experimental results are presented by an example of burning acetylene in water with initiation of gas ignition in the bubble by an electric discharge. A model of dynamics and explosion of a single bubble is used for estimation the efficiency of the process under consideration. The energy of the acoustical radiation and characteristic times of the heat transfer processes are calculated. The experimental results and theoretical calculations show that it is possible to pass to the new principles of operation of heat generators.

Keywords: burning of gases; hydrocarbon fuels; water-based heat carrier; electric discharge; heat generator

1 Introduction

The problem of energy saving is urgent in all countries of the world. Energy saving is most frequently considered in terms of energy consumption. Saving of natural energy resources at the stage of production of thermal and electrical energy, however, is even more important. The technology of obtaining electrical energy and heat by burning hydrocarbon fuels experienced practically no changes in recent years. The technology of heat transfer to the heat carrier was mainly improved by means of improving the characteristics of heat-exchange systems. Available heat exchangers prevent increasing specific power of heat generators because of the development of crisis phenomena during liquid boiling [1]. New principles and approaches are needed for a further increase in efficiency of heat transfer to the heat carrier with simultaneous reduction of biosphere pollution. At the moment, burning of hydrocarbon fuels is arranged in industrial heat generators in the regime of continuous combustion with exhaustion of combustion products into the atmosphere.

A possibility of heat transfer from combustion products directly to a water-based heat carrier in the regime of pulsed burning of combustible gases in bubbles is considered in the paper. Such an approach allows heat losses at the stage of fuel combustion and the amount of wastes exhausted into the atmosphere to be substantially reduced. A method of ignition of acetylene–oxygen bubbles by an electric discharge in water is tested experimentally.

2 Experimental Setup

The arrangement of experiments is illustrated in Fig.1. A 150 × 150 × 150 mm cavity 1 was filled by water. A tube-electrode 2 insulated from outside was mounted vertically in this cavity. A bubble 3 with a stoichiometric acetylene–oxygen mixture was ejected into water through this tube. A 0.3%–0.6% water solution of usual table salt was used to provide an electric breakdown in the bubble. The gas mixture in the bubble was ignited by applying voltage to the tube-electrode from a capacitor with a capacity $C = 100\ \mu$F with the use of an electromagnetic switch S. The capacitor was charged with a voltage source 5. The inductance in these experiments was $L = 7.7$ mH. The discharge current was monitored by a Tektronix TDS-210 oscillograph 6 connected to a shunt $R = 0.2\ \Omega$. The second ray of the oscillograph was used to monitor the voltage U. Shadowgraphs of the hydrodynamic processes were taken with a MotionXtra HG-LE high-speed video camera. The experiments were performed with a stoichiometric mixture of acetylene with oxygen ($C_2H_2 + 2.5O_2$). The gas mixture was ejected into water with the conductivity $\approx 1\ \Omega^{-1}\cdot\ m^{-1}$ through the tube-electrode with the outer diameter $d_c = 2.1$ mm and inner diameter $d_{in} = 1.5$ mm. The bubble diameter was $d \approx d_c$, and the voltage of 350–500 V was supplied to the electrode. To prevent flame propagation in the gas pipe, a fire barrier was mounted in the tube.

3 Experimental Results

The dynamics of expansion and oscillations of the bubble with gas combustion is qualitatively similar to the bubble dynamics in the case of HE explosion in water. In our experiments, combustion of the acetylene– oxygen mixture in the bubble increased the initial bubble diameter d to $D = (3\ Í\}\ 0.1)d$, and the results were well reproduced. Fig.2 shows the typical frames and oscillogram of the process for one cycle of gas ignition and burning in a bubble with the initial diameter $d = 2$mm(a) and two frames of subsequent fragmentation of bubbles (b). In this arrangement of experiments, the electric breakdown in the gas occurs inside the bubble, between the tube electrode and electrolyte, which ignites the gas mixture in the bubble. The initiation energy in the experiments described here is 2×10^{-2} J. In our test conditions, the bubble expands to the diameter $D = 6$ mm during the time of 0.3 msec and then starts to collapse approximately back to its initial diameter, losing its symmetry. The collapse and subsequent motion are accompanied by formation of a toroidal vortical bubble cluster. The velocity of separation of the first bubble cluster from the electrode is $v_b \approx 10$–15 m/sec. In the course of motion of the toroidal bubble cluster, it is broken to the size $d_i = 0.1$–0.3 mm. In 10 msec, the region along the direction of motion of the bubble cluster increases approximately to 15 mm, which corresponds to the mean velocity of the water flow carrying small bubbles $v_w \approx 1.5$ m/sec. It follows from the records obtained that a second bubble is formed at the instant when the bubble with the burnt gas collapses (frame 8). In this arrangement of experiments, the second bubble is generated by the electric discharge energy; this is seen in the oscillograms in the time interval from 0.7 to 1.2 ms. Fig.2b shows some instants of further

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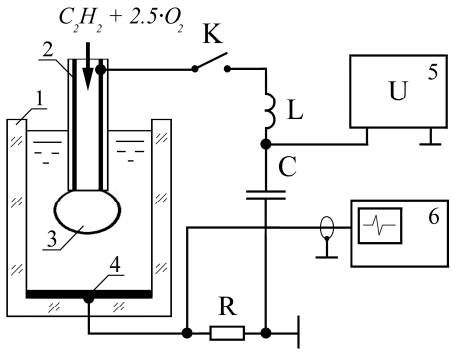
motion of bubble clusters formed from the generated bubbles (the time in the frames shows the duration after the initiation moment).



1–Plexiglas cavity; 2–tube-electrode; 3– bubble with the acetylene–oxygen mixture; 4–opposite electrode; 5– unit for charging the capacitor *C*; 6– digital oscillograph; electromagnetic switch is denoted as S, Parker's shunt as *R*, and inductance as *L*.

Fig.1 Arrangement of experiments

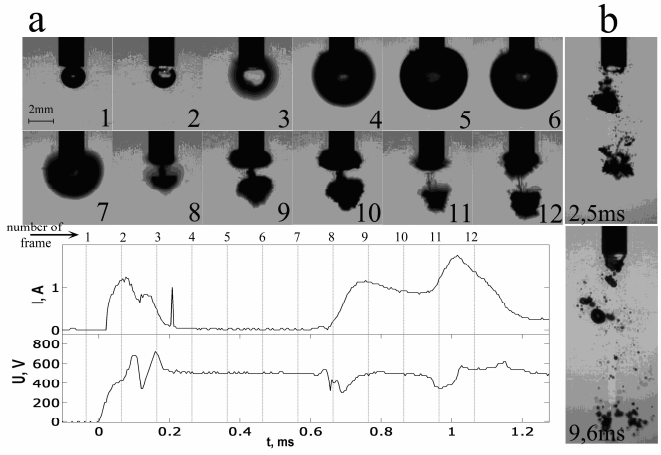


Fig.2 (a) Frames of one cycle of burning of the acetylene–oxygen bubble in water correlated with the electrical parameters of current and voltage; (b) subsequent fragmentation of bubbles; frame rate 104 frames/sec

4 Analysis of Experimental Results

The energy of point ignition of the $C_2H_2 + 2.5O_2$ mixture at atmospheric pressure was estimated in [2] as $E \approx 10^{-6}$–10^{-7} J. Recalculation to annular (d = 1.5 mm) ignition yields the minimum energy $E \approx 10{-}4{–}10{-}5$ J. The measured current and voltage in our experiments showed that the ignition energy was $2{\times}10^{-2}$ J. Apparently, the major part of energy was spent on heating and evaporating the electrolyte in the zone of junction of the bubble and the outer surface of the tube-electrode. Relative expenses on bubble ignition were 2%–3% of the released chemical energy. These expenses will decrease with increasing size of the initial bubble. As the gas burns in the reaction $C_2H_2 + 2.5O_2 = 2CO_2 + H_2O + 1318$ kJ/mole, the amount of energy Q = 0.94 J is released in the bubble with the diameter d = 2 mm. The time of gas burning in the bubble was approximately calculated under the assumption that the temperatures ahead of and behind the front of the spherical flame are constant, and the flame velocity relative to the gas is 10 m/sec. Gas compression ahead of the flame was taken into account. It turned out that the time of gas combustion in the bubble was approximately 13 μs.

The estimate of bubble-wall acceleration in accordance with the energy conservation law showed (the velocity was assumed to be a linear function of time) that the wall is accelerated to 8 m/sec during gas combustion, the bubble radius increases by 5%, and the bubble volume increases by 15%. The maximum pressure in the bubble is expected to be lower than the pressure during combustion in a constant volume approximately by the same value, because expansion of combustion products is almost isothermal. The pressure increases thereby only to ≈15 atm. The bubble continues to expand, and the pressure decreases. The maximum bubble size can be estimated on the basis of the work performed by the gas during adiabatic expansion. At the effective adiabat index of 1.1, the maximum bubble diameter is approximately 3.9 times greater than the initial diameter, whereas the experimental value is D/d = 3. The difference is partly associated with heat transfer to water in the course of expansion and also with departure of some part of the burnt gas to the input tube. A question arises: How rapidly is the heat from the burnt gas transferred to water? If the bubble were not destroyed, it would cool down during the time $t_1 \approx 10^{-2}$ s. In our case, the broken bubbles transfer the heat during the time $t_2 < 10^{-4}$ s. The degree of bubble fragmentation can be estimated on the basis of the Weber number. For the relative velocity of ≈10 m/s, the

Weber number is $W_e \approx 10^3$, which is two orders greater than its critical value. The bubble is broken into smaller bubbles with the mean size $d_i \approx 0.3$ mm. It is fragmentation of the initial bubbles in our experimental arrangement that leads to drastic enhancement of heat transfer. The filming and current oscillograms show that nucleation of the next bubbles owing to discharges on the tube-electrode with subsequent breakdown in the bubbles can occur automatically at the instants of separation of the previous bubbles. Thus, simultaneous ignition of the gas in N bubbles can occur in the regime of electrohydrodynamic selfsynchronization of breakdowns in these bubbles [3-4].

This feature shows the prospects of development of pulsed heat generators based on the proposed principle of initiation and burning of hydrocarbon fuels. The upper limit of the generator power is constrained only by the frequency of fuel ejection into water. It is determined by the period of oscillations of the initiated bubbles. For instance, if the frequency of burning of the bubbles is 1 kHz and 25,600 tubes-electrodes are placed on the area of 1 m^2, the mean specific power of such a generator is ≈25 MW/m^2. In this case, fragmentation of the initial bubbles is assumed to occur independent of the neighboring bubbles. All thermal energy remains in water. Note that this estimate was made for a particular case with the test conditions used in our experiments. Structurally, more powerful and compact devices with pulsed burning of fuels in a water-based heat carrier are possible. Such devices have no heat-conducting metallic elements, which prevent the increase in specific power because of development of crisis phenomena of boiling in the liquid. Electric breakdowns with gas ignition in the bubbles occur at the instants when the electrode cross sections are overlapped with expanding bubbles.

4.1 Energy of Acoustical Radiation, Caused by Bubble Explosion

It is known that explosion and subsequent expansion of a bubble led to the emission of compression waves. Typical emission of a weak shock wave during first bubble oscillation, caused by bubble explosion, is shown in Fig.3. In this experiment gas explosion occurs after bubble compression behind a shock wave in liquid. Similar shock wave will be emitted after bubble explosion caused by electric discharge. To evaluate the efficiency of the heat generator under consideration, the energy of the acoustical radiation should be estimated.

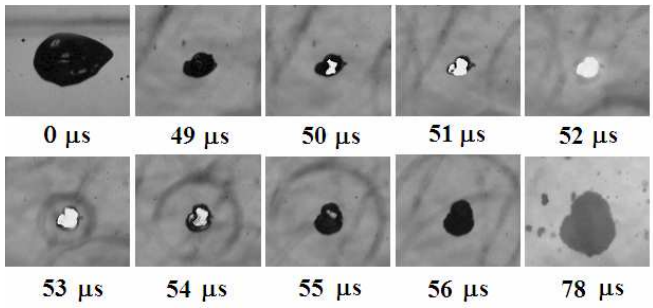


Fig.3 Shock induced explosion of a single bubble and subsequent emission of acoustical waves. Oxygen bubble in cyclohexane. The incident shock wave exerts impact on the walls of the bubble at $t = 0$ (experiment [5], see also [6, 7])

The following scenario will be considered. The single spherical bubble contains stoichiometric hydrogen-oxygen mixture and is located in water. Initial pressure and temperature of two-phase system are 5 atm and 298 K respectively. It is assumed that the ambient pressure remains constant. Bubble ignition and instantaneous explosion of the gas occurs at the initial moment in time. The gas pressure, temperature, and molar mass experience a drastic change. The gas mixture instantaneously acquires the state of chemical equilibrium, which is always shifted because of bubble oscillations. The first jump of gas parameters is instantaneous and therefore occurs at the constant volume of the bubble. As a result of ignition, the gas pressure becomes higher than the ambient pressure, and the bubble performs several gradually decaying oscillations; at the end, the gas pressure becomes equal to the liquid pressure.

The calculations were performed by the model of explosion and oscillations of a single bubble, which was previously proposed in [8-11]. The model implies that there is no inter-phase transfer processes between gas and liquid surface of a bubble.

The thermodynamic parameters of the mixture and the shift of chemical equilibrium are described by the kinetic model previously proposed in [12-14]. The bubble dynamics was calculated by the commonly used Rayleigh equation with additional terms that take into account acoustic radiation of the bubble.. The initial diameter of the bubble was assumed to be 3.2 mm.

The calculation results are plotted in Fig.4.

Figs. 4(a) and (b) show the calculated dynamics of the bubble from its ignition to complete decay of bubble oscillations. These figures do not illustrate the process under consideration in detail; hence, Figs. 4(c–e) show the dynamics of bubble parameters during several first oscillations. The pressure and temperature jumps are caused by instantaneous ignition.

Fig.4(f) shows the P-V diagram of the process considered. The initial parameters of the gas correspond to point A. As a result of ignition, the parameters of the mixture jump instantaneously from point A to point B. An instantaneous increase in pressure leads to bubble oscillations. The parameters of the mixture change along the adiabatic (isentropic) curve of the chemically equilibrium gas BDC. First, the parameters move downward along the curve in the direction indicated by the arrow. Then, owing to bubble oscillations, the parameters of the mixture also perform oscillations with respect to point D. The amplitude of oscillations

continuously decreases. The final point of the process corresponds to point D, which is marked by the vertical arrow. The parameters at points A, B, C, D are:

A: P = 5 atm, T = 298.15K, $\rho = 2.42 \cdot 10^{-3}$ g/cm^3, V = 413.4 cm^3/g, μ = 12 g/mole;

B: P = 50.38 atm, T = 3833 K, $\rho = 2.42 \cdot 10^{-3}$ g/cm^3, V = 413.4 cm^3/g, μ = 15.34 g/mole;

C: P = 1.283 atm, T = 2796 K, $\rho = 9.32 \cdot 10^{-5}$ g/cm^3, V = 10729 cm^3/g, μ = 16.90 g/mole;

D: P = 5 atm, T = 3134 K, $\rho = 3.15 \cdot 10^{-4}$ g/cm^3, V = 3176.1 cm^3/g, μ = 16.34 g/mole.

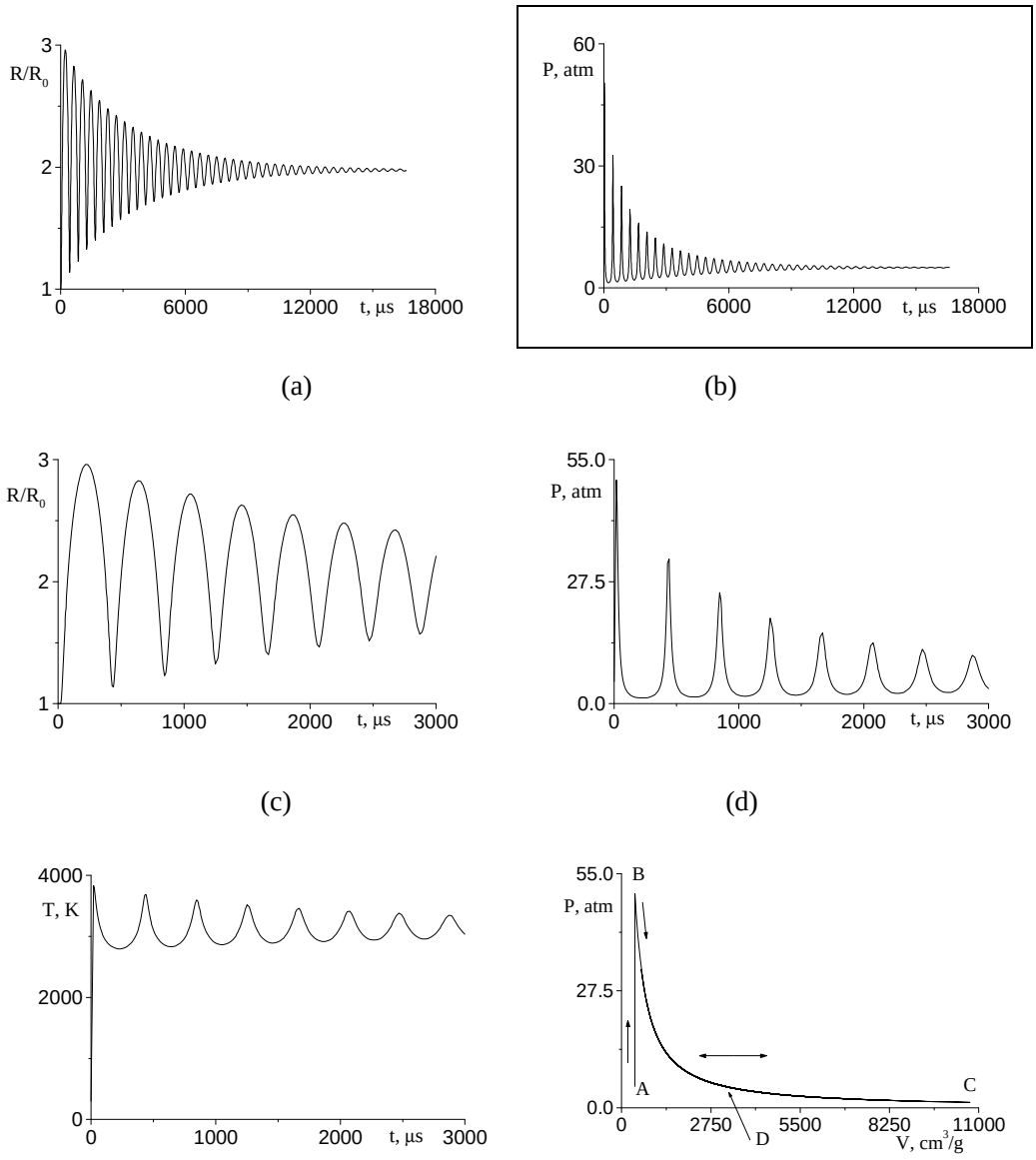


Fig.4 Bubble dynamics and gas parameters after ignition

The mechanical efficiency (η) of the cycles under consideration equals the difference between the enthalpies of the final and initial states, divided by the reaction heat: $\eta = (I_2 - I_1)/Q$ (here, I_2 and I_1 are the final and initial enthalpies of the gas, respectively), Q is the heat release of chemical reaction. According to the model [12, 13] $Q = E(1/\mu_0 - 1/\mu)$, μ_0 is the initial molar mass of the gas, E is the mean energy of dissociation of generalized reaction products, Q_{max} is the maximal heat release of chemical reaction, $Q = Q_{max}$ if $\mu = \mu_{max}$. According to the results of calculations, presented above (see the parameters of points A and D) η = 22.7 %. It means that 22.7 % of the energy of explosion will be transformed into the energy of acoustical waves. Such energy can be partially absorbed inside the liquid volume after reflections of these waves from walls of the volume and inhomogenities inside the liquid volume. Results of calculations η for stoichiometric acetylene–oxygen mixture at P_0 = 1atm are similar for the calculations, presented above.

4.2 Heat Release of Chemical Reaction vs the Ignition Energy

One of the requirements to the heat generator is that the energy required for its operation should be much lower than the energy released in the course of the generator operation (heat performed by the generator). Let's compare the energy of electric discharge

and the total heat release of chemical reaction inside the bubble Q_Σ at P_0 = 1 atm. Note that $Q_\Sigma = Q_{max}\ 4/3{\cdot}\pi R_0^3\rho_0$. The specific heat of chemical reaction will be maximal if the temperature of gas will be equal to the temperature of liquid owing to cooling of gas by inter-phase heat transfer process, and, therefore, $\mu = \mu_{max}$ [12-13]. According to [12, 13] $Q_{max} = E(1/\mu_0 - 1/\mu_{max})$. For stoichiometric hydrogen-oxygen mixture μ_{max} = 18 kg/kmol, μ_0 = 12 kg/kmol and E = 109680.5 cal/mol. For 2 mm bubble the heat release of chemical reaction is 0.4 J. This energy is essentially less, than the ignition energy in our experiments (10^{-2} J).

4.3 Estimation the Characteristic Time of Inter-phase Transfer Process

Let's calculate the characteristic time τ of cooling of gas owing to inter-phase heat transfer process. According to [15-16], $\tau = R^2/(\pi^2\lambda/\rho C_V)$, where R is the radius of bubble, λ is the heat transfer coefficient and C_V is the heat capacity of gas at constant volume. The following formula for calculation the heat transfer coefficient is used [17]: $\lambda = \lambda_0(T/373)^{1.5}$, where $\lambda_0 = 1.7{\cdot}10^{-2}$ J/(m·s·K) is the heat transfer coefficient at 373 K. Let's assume for estimations that ρ = 0.3 kg/m^3 and T = 3000 K. According to [12] $C_V \approx 1.5{\cdot}10^4$ J/(K·kg). With the help of the formula, presented above, it is found that τ = 1.1 ms and 28 ms at R = 1 mm and R = 5 mm respectively. After the time period, equals to approximately 8τ [18], the temperatures of the gas and surrounding liquid should be equal each other. For the bubbles under discussion, such time periods are 8.8 ms and 224 ms respectively. These time periods are essentially shorter than the characteristic time of operating cycle of the heater.

5 Conclusions

A principal possibility of pulsed burning of hydrocarbon fuels directly in the water-based heat carrier, aimed at creating heat generators of a new type, is experimentally demonstrated.

A model of dynamics and explosion of a single bubble is used for estimation the efficiency of the process under consideration. The energy of the acoustical radiation and characteristic times of the heat transfer processes are calculated. It is shown that the heat release of chemical reaction is essentially less than the energy of bubble explosion initiation. The characteristic time of inter-phase heat transfer process is essentially shorter than the characteristic time of operating cycle of the heater. Approximately 20 percents of the energy of explosion is transformed into the energy of acoustical waves. Such energy can be partially absorbed inside the liquid volume after reflections of these waves from walls of the volume and inhomogenities inside the liquid volume.

The experimental results and theoretical calculations show that it is possible to pass to the new principles of operation of heat generators. Moreover, such an approach allows heat losses at the stage of fuel combustion and the amount of wastes exhausted into the atmosphere to be substantially reduced.

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References

[1] Kutateladze S S, Nakoryakov V E. Heat and Mass Transfer and Waves in Gas–Liquid Systems. Novosibirsk: Nauka,1984. (in Russian)

[2] Ivanov B A. Physics of Acetylene Explosion. Moscow: Khimiya, 1969 (in Russian)

[3] Teslenko V S, Medvedev R N, Drozhzhin A P. Self-synchronization of electrohydrodynamic selfsustained oscillations with multiple discharges in an electrolyte. Pis'ma Zh Tekh Fiz, 2007, 33(19):55–63. URL: http://www.ioffe.ru/journals/ pjtf/2007/ 19/p55-64.pdf.

[4] Medvedev R, Teslenko V, Drozhzhin A. Electrohydrodynamic self-synchronization of self-oscillations on two diaphragm current concentrators in electrolyte. Phys Lett A, 2008, 373: 102–106. URL: http://www.swsl.newmail.ru/publ/PLA18400.pdf.

[5] Mitropetros K. Shock induced bubble explosions in liquid cyclohexane. BAM-Dissertationsreihe, Band 11. Federal Institute for Materials Research and Testing (BAM), Berlin, 2005. ISSN 1613-4249, ISBN 3-86509-360-4.

[6] Mitropetros K, Fomine P, Hieronymus H. Verfahren und Vorrichtung zur Bestimmung der Zundbedingungen fur ein Gasgemish. German Patent DE 102005015501 B3 2006.11.30.

[7] Mitropetros K, Fomin P A, Steinbach J, et al. Explosions of oxygen bubbles in cyclohexane. Chemical Engineering Journal, 2004, 97(2/3):151-160.

[8] Kedrinskii V K., Fomin P A, Taratuta S P. Dynamics of single bubble in a liquid in the presence of chemical reactions and interphase heat and mass exchange. Journal of Applied Mechanics and Technical Physics, 1999, 40(2): 292-299.

[9] Fomin P A, Vasil'ev A A. Detonation wave modeling in typical bubble systems. Journal of Loss Prevention in the Process Industries, 2001, 14: 521-526.

[10] Fomin P A, Mitropetros K S, Taratuta S P. Hieronymus H. Modeling of detonation wave initiation, limits and hazard of chemically active bubbles// Doerffer P. Internal Flows, Vol. 2. IFFM Publishers, 2001: 925-933.

[11] Fomin P A, Mitropetros K S, Hieronymus H. Modeling of detonation processes in chemically active bubble systems at normal and elevated initial pressures. Journal of Loss Prevention in the Process Industries, 2003, 16(4): 323-331.

[12] Nikolaev Yu A, Fomin P A. Analysis of equilibrium flows of chemically reacting gases. Combustion, Explosion and Shock Waves, 1982, 18(1):53-58.

[13] Nikolaev Yu A, Zak D V. Agreement of models of chemical reactions in gases with the second law of thermodynamics. Combustion, Explosion and Shock Waves, 1988, 24(4): 461-464.

[14] Fomin P A, Trotsyuk A V. An approximate calculation of the isentrope of a gas in chemical equilibrium. Combustion, Explosion and Shock Waves, 1995, 31(4): 455-457.

[15] Frank-Kamenetskii D A. Diffusion and Heat Transfer in Chemical Kinetics. Plenum Publ, 1969.

[16] Landau L D, Lifshitz E M. Fluid Mechanics.London: Butterworth-Heinemann, 1987

[17] Kikoin I K. Tables of Physical Quantities. Moscow: Atomizdat, 1976. (in Russian)

[18] Carslaw H S, Jaeger J C. Conduction of Heat in Solids. 2nd ed. Oxford: Clarendon Press, 2001.